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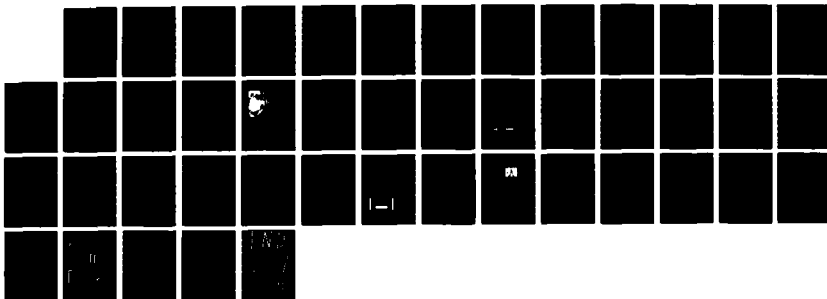
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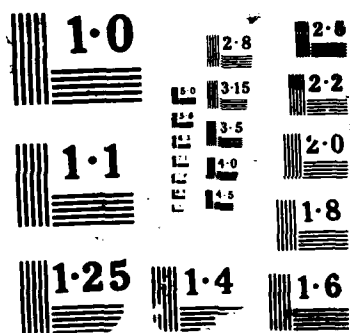
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**NONCONVENTIONAL OPTICAL TECHNIQUES
FOR OPTICAL WAVEFRONT PROCESSING**

M. M. Salour

Tacan Aerospace Corporation
2111 Palomar Airport Road
Carlsbad, CA 92008

June 1987

Final Report

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AIR FORCE WEAPONS LABORATORY
Air Force Systems Command
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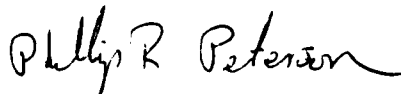
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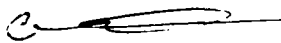
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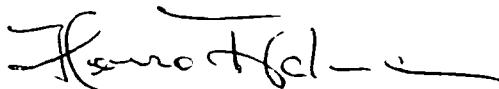


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This report describes the design and construction of an optically pumped semiconductor laser oscillator with the following specifications: 1) Operating wavelengths, 414 nm and 680 nm, interchangeable (i.e., requires a change in optical setup and the pump source, but no change in the cavity design); 2) CW power, nominal 30 mW each line; and 3) Tuning range of ± 30 nm. The laser includes all external ring cavity components, cooling (nonliquid N ₂), and provisions were made for mounting line narrowing and tuning elements. Ancillary equipment list, operating and instruction manuals were also provided.			
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I. RESEARCH OBJECTIVES

The aim of this work was to investigate a variety of techniques and concepts in the study of nonconventional optical techniques for wavefront processing and adaptive optics. These ideas were conceived as a result of the work on the development and invention of the first optically pumped semiconductor laser in external cavities (five patents), and optical signal processing and compensation of distorted signals due to the group velocity dispersion in optical fibers (one patent).

The design and construction of an optically pumped semiconductor laser oscillator has been completed with the following specifications:

- a. Operating wavelengths, 414 nm and 680 nm, interchangeable (i.e., requires a change in optical set up and the pump source but no change in the cavity design)
- b. Continuous wave power, nominal 30 mW each line
- c. Tuning range of ± 30 nm

The laser includes all external ring cavity components, cooling (nonliquid N_2), and provisions were made for mounting line narrowing and tuning elements. Ancillary equipment list, operating and instruction manuals were also provided.

The first optically pumped mode-locked $Al_{0.3}Ga_{0.7}As/GaAs$ multiple-quantum-well (MQW) laser in external cavity was also reported. The MQW structure with a total thickness of 5 μm was grown by molecular beam epitaxy (MBE) on a Si-doped GaAs substrate and was synchronously pumped by a mode-locked Kr^+ -laser (82 MHz) at 647.1 nm. The MQW laser emitted 10 ps pulses at 8085 Å with peak powers as high as 6 W. The demonstrated MQW laser combines desirable properties of quantum wells with advantages of an external cavity, such as specific bandgap design with high beam quality and the possibility of intracavity tailoring of the laser beam.

Finally, intracavity phase conjugation, and an externally self-pumped phase conjugate resonator were demonstrated. Mode-locked operation of Si-doped bulk GaAs in external cavity was achieved by synchronous pumping with a Kr^+ laser at 647.1 nm. High beam quality and peak powers of up to 3.3 W are unique features of this laser. The spontaneous spectrum is narrower than those of dyes, allowing a stabilized single-frequency operation with fewer wavelength selective elements, while tunability over a range of 300 Å was achieved by varying the temperature.

These outlined achievements were the result of both theoretically and experimentally testing ideas. The first tunable CW radiation from a bulk semiconductor platelet in external cavities has been successfully demonstrated. Thus far, tunable CW laser action in both mode-locked and unmode-locked configurations has been achieved. The gain media were platelets of Cds, CdSe, InGaAsP, and HgCdTe. In addition, the first optically pumped semiconductor laser in a ring cavity for both CW and mode-locked configurations was demonstrated. Pulses as short as 2.8 ps and continuous tunability between 500 nm and 2.1 μm , a range which is not entirely available from dye lasers were generated. Because of the lack of dye jet fluctuations, semiconductor lasers provide narrower line widths than dye lasers, and samples mounted adjacent to each other can be changed easily and quickly to provide tunability over a broad range. Furthermore, a long shelf-life and the lack of orientation and bleaching makes these lasers more practical than F-center lasers for many applications.

II. BACKGROUND

The surge of interest in the field of nonlinear optical techniques involving phase conjugation, adaptive optics, deformable mirrors, spatial and temporal information processing calls for novel, nonconventional techniques for real-time information processing of electromagnetic fields -- a field recently opened up by virtue of the all optical nonlinear (high power laser) mixing techniques and preferably free of electromechanical components and/or electronic feedback networks. Such techniques can possess much greater spatial and/or temporal bandwidths, reduced system complexity as well as lower cost, size, and weight than their conventional counterparts. The purpose of the program was to study and develop a variety of novel techniques involving nonconventional adaptive optics degraded due to turbulence, and investigate novel nonconventional compensation systems. These studies involved both theory and experiment. Various techniques were used involving the use of phase conjugate optics for information processing, and its usefulness for restoring spatial information transmitted through the atmosphere was explored. This involved intracavity phase conjugates, a self-pumped system utilizing a variety of material as a gain medium (as a low power adaptive optics) followed by a chain of amplifiers. Applications in the areas of optical computing, real-time image and temporal signal processing, real-time adaptive optical systems, coherent image amplification, pointing and tracking, filtering, laser fusion, optical communication systems, and ultralow-noise quantum optical detectors are some examples of the diverse potential outcome of the research.

The common denominator of phenomena and applications in optical phase conjugation is that a number of waves -- usually two or three, but possibly more -- are incident on a nonlinear medium, which then radiates a new wave whose frequency is equal to some particular combination (i.e., sum and difference) of the input frequencies. The amplitude of the radiated field is proportional to the complex conjugate of one of the input amplitudes. Many of the applications and demonstrations involve the phase or wavefront reversal of a given electromagnetic wave, which is equivalent to performing the operation of complex conjugation on its complex spatial amplitude. Many investigators have demonstrated a variety of applications of optical phase conjugations using nonlinear optical techniques, and nonlinear optical phase conjugation (NOPC) has emerged as a technique giving rise to many fascinating

phenomena and applications. These include real-time adaptive optics (compensation of aberrated fields due to propagation or image transmission through distorting media), optical computing, image processing, optical signal processing in both spatial and temporal domain, interferometry, nonlinear laser spectroscopy, and ultralow noise detection -- to name just a few. The unique reflective properties associated with optical phase conjugation are accomplished by three- or four-wave mixing, stimulated scattering processes, or pseudoconjugators. Historically, the thrust of optical phase conjugation (OPC) has dealt with the compensation of distortions due to the propagation of electromagnetic fields through various aberrating media (e.g., turbulent atmospheres). The most commonly used approach to achieve this goal is referred to as adaptive optic techniques. Portions of this proposed research will utilize the NOPC technique which will not only provide an alternative technique to many of these goals but should also lead to many new classes of novel, all-optical information processors.

The phase conjugator or a phase conjugate mirror (PCM), ideally gives rise to a converging conjugate wave that precisely retraces the path of the incident probe wave and, therefore, propagates in a time-reversed sensor back to the same initial point source. This profound effect of the PCM -- the ability to temporally reverse the evolution of an input wave (or equivalently, to perform the operation of both wavefront inversion and propagation reversal) -- has found important application in adaptive optics.

The spatial and spectral properties of a PCM generated by nonlinear optical mixing has resulted in myriad potential applications. All such exciting applications rely on a PCM's complex conjugation operation (upon the spatial part of the incident wave's complex amplitude). The ability of a PCM to yield a time-reversed replica of an incident monochromatic field of arbitrary spatial phase and/or polarization has resulted in a series of important improvements in image processing and laser communications, by compensating for phase distortion through atmospheric turbulence or poor quality optical elements.

A set of potential spatial domain applications of nonlinear optical phase conjugation using four-wave mixing (FWM) processes has been introduced. This involved the incidence of three input waves onto a medium, with the nonlinear generation of an output field whose amplitude is proportional to the complex conjugate (and is a time-reversed replica) of one of the input fields (Figure 1).

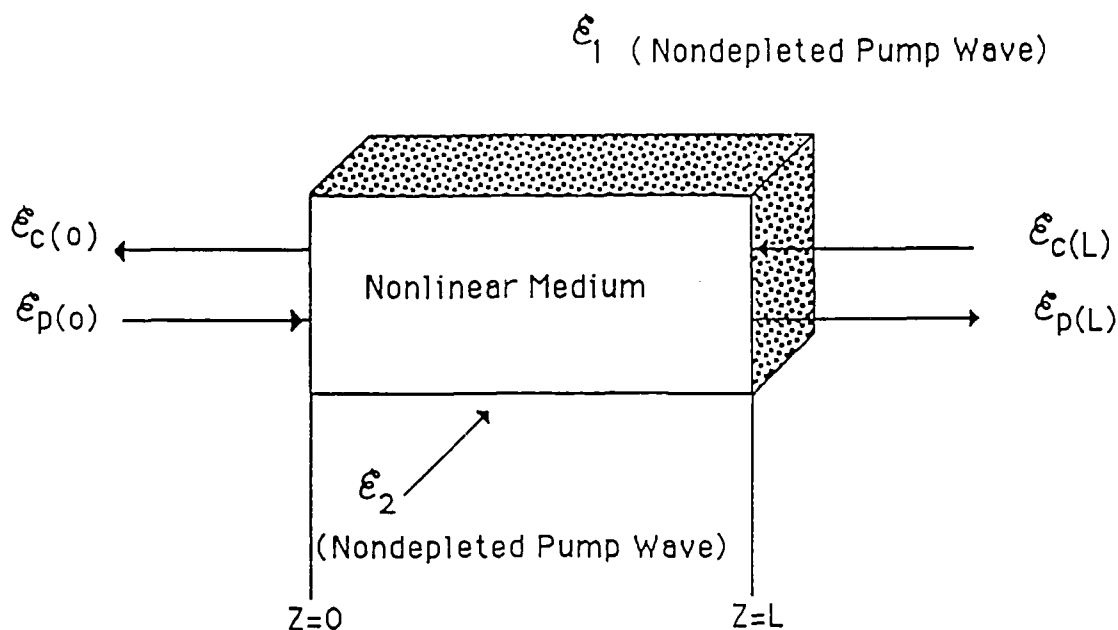


FIGURE 1

Nonlinear Optical Phase Conjugation Using Four-Wave Mixing

In Figure 2:

$$E_1(\vec{r}, t) = \frac{1}{2} E_1(\vec{r}) e^{i(\omega_1 t - k_1 z)} + c. c. \quad (1)$$

and

$$E_p(\vec{r}, t) = \frac{1}{2} E_p(\vec{r}) e^{i(\omega_p t - k_p z)} + c. c. \quad (2)$$

two pump waves E_1 and E_2 (each at ω) and a probe wave E_p (at ω) are incident upon a medium possessing a third order nonlinear optical susceptibility, $\chi^{(3)}$. The conjugate wave E_c is radiated in the forward direction. In the scheme as shown, the pump waves can be generated from a single pump beam, with angular separation of the conjugate wave from the probe field. The three input waves shown in Figure 2 result in a third

order nonlinear polarization given by

$$P_{NL} = \frac{1}{2} \chi^{(3)} \epsilon_1(\vec{r}) \epsilon_2(\vec{r}) \epsilon_p^*(\vec{r}) \exp \{ i [\omega_1 + \omega_2 - \omega_p] t - (\vec{k}_1 + \vec{k}_2 - \vec{k}_p) \cdot \vec{r} \} + c. c \quad (3)$$

where $\chi^{(3)}$ is the third-order nonlinear optical susceptibility that characterizes the interacting medium. The fields $\epsilon_{1,2}(\vec{r})$ are pump waves at frequencies $\omega_{1,2}$. The probe wave, $\epsilon_p(\vec{r})$, assumed to be weak, is at frequency ω_p and, in general, consists of a complex spatial (and/or polarization) wavefront, whose conjugate replica is sought. The generation of backward-going phase-conjugate replicas using degenerate four-wave mixing (DFWM).

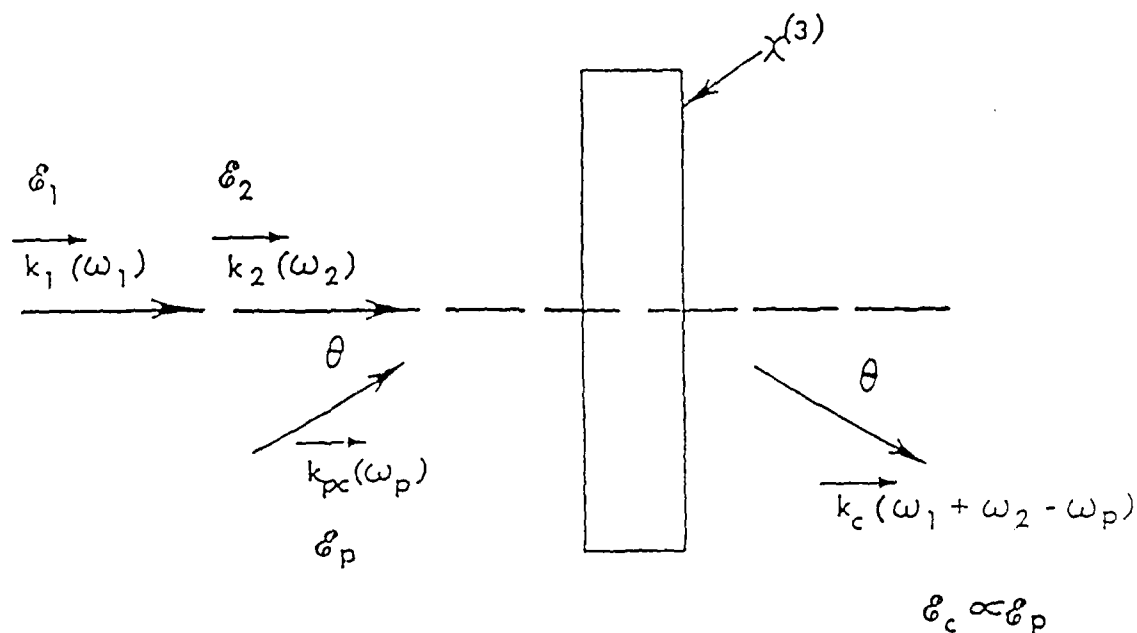


FIGURE 2
Third Order Nonlinear Polarization

This process can apply regardless of the input angle of the probe wave. Hence, the interaction can time-reverse the propagation of an arbitrary input probe wave (at frequency ω). Apparently, this interaction comes closest to the operation of an ideal PCM. It also is capable of yielding a time-reversed replica of amplitude greater than that of probe wave. Thus an amplified PCM can be realized and coherent amplification of the forward-going probe is possible, as is the potential of a mirrorless, optical parametric oscillation mode.

The nonlinear optical mixing materials used in the many experimental demonstrations have been selected from all states of matter (liquids; solids, including semiconductors; vapors and gases; liquid crystals; plasmas; aerosols; etc.) and have been realized using laser sources spanning the entire optical spectrum. In fact, the conceptual extension of these techniques to other portions of the electromagnetic spectrum should follow. Optical sources (both CW and pulsed) covering twelve decades of output power (megawatts to microwatts) have been used to this end. Although still in its infancy -- the field is about a decade old -- the applications envisioned are far reaching in their scope, as is the use of some of these processes to the field of nonconventional adaptive optics which is an exciting and wide open field.

In this research, the unique reflective properties associated with optical phase conjugation (accomplished by four-wave mixing in an external cavity) were used. Such cavities can consist of one mirror being a more or less ideal PCM.

APPENDIX A

COMPACT CdSe LASER WITH MICRO-MINIATURE CRYOGENIC REFRIGERATOR

1. Contributing Authors

B. Valk, D.J. Olson, and M.M. Salour

2. Abstract

A microminiature refrigeration system allowing precise temperature control above 77 K has been tested successfully as a compact Dewar to achieve the necessary cryogenic temperatures to operate optically pumped semiconductor lasers in an external cavity.

3. Introduction

Recently, lasing of optically pumped CdSe and many other direct bandgap semiconductor materials has been demonstrated in an external cavity in both mode-locked and continuous operation.¹⁻³ These lasers can be operated in many ways like dye lasers with an even greater wavelength range. Hence, for various wavelength regions and applications which do not allow dye jets, they are an attractive alternative for medium power requirements of up to 40 mW. However, the problem inherent in the design of semiconductor lasers with an external cavity is the need for cryogenic temperatures. At higher temperatures the exciton photon coupling increases, causing a decrease in the relative strength of the luminescence lines and a spectral broadening. The change of the bandgap with temperature and the according shift of the emission wavelength has been used for tuning purposes but most optically pumped semiconductor lasers operate³ only below 130 K. To provide these low temperatures, several dewar designs have been tested,^{4,5} but they can be used only at specific liquid gas temperatures and suffer from bulkiness.

These disadvantages are overcome by using a micro-miniature refrigeration (MMR) system from MMR Technologies Inc. Besides being compact and light weight, this system allows for a precise temperature setting above 77 K. The

K7702/IIB system used is a Joule-Thompson gas expansion refrigerator. Prepurified nitrogen gas at high pressure (1800 psi) expands through capillaries producing liquified nitrogen under a cold pad. Temperatures higher than 77 K are controlled by a resistive heater and a silicon diode temperature sensor built into the pad⁶.

4. Experiment and Results

We tested this system with a CdSe laser which was synchronously pumped by a mode-locked Kr^+ -laser at 647.1 nm. The laser setup consists of an $R=0.90$ output coupler, a polarizing beamsplitting cube inside the cavity to separate the pump and CdSe laser beam, and a 10X microscope objective (Leitz) to focus the pump beam onto the CdSe platelet inside the dewar of the MMR system which is shown in Figure 1. The platelets were mounted with a very thin layer of silicon oil onto a 12.7 mm diameter and 1 mm thick dielectric coated sapphire mirror. This mirror was attached with vacuum grease to a thin brass clip which could be slid onto the cold pad. The cool-down time with this probe was about 35 minutes. The small vacuum chamber of the MMR system was replaced by a specially designed chamber with removable windows for cleaning purposes and with appropriate dimensions (73x40x15mm) to keep the distance between mirror and chamber window within the 6.8 mm working distance of the objective. Furthermore, the dewar design allows its operation in a ring cavity. The refrigerator was mounted on a tilt table and a x,y,z translation stage. Due to the compactness and light weight of the refrigerator, all alignment procedures were more convenient than for lasers operated with a liquid nitrogen dewar. It turned out that the proper operation of the MMR refrigerator was very sensitive to the vacuum which has to be better than 10 mtorr. At slightly higher vacuum pressures the probe usually started to warm up after one-half hour of operation at 77 K.

Figure 2 shows the average output power of the mode-locked CdSe laser versus pump power. The output power increases linearly with pump power and the conversion efficiency is 5%. A stable output power of up to 10 mW could be achieved consistently. A sudden damage of the lasing spot was often observed

when the pump power exceeded 200mW rather than saturation effects. This damage results most likely from light induced defects in the CdSe. Such defects could be generated easily in other semiconductors⁷ when the average pump intensity exceeded 0.5 MW/cm^2 . However, it was possible to find some spots giving maximum average powers as high as 25 mW for a short time when pumped with 310 mW. The temperature was varied between 77 K and 111 K without changing the output power characteristics of the laser. This was surprising since we expected a more significant decrease of the output power with increasing temperature.

The wavelength changed with temperature from 7015 Å to about 7160 Å as shown in Figure 3. Besides the main laser line, due to the free spectral range of the Fabry Perot etalon formed by the CdSe platelet, a second and third line appears about 30 Å and 60 Å apart. The two different spectra at 92 K and the shift of the main laser line by about 15 Å were produced by changing the cavity alignment. These results show that the performance of the temperature tuning in terms of reproducibility and precise wavelength tuning is fairly poor, so a birefringent filter inside the cavity is recommended. Tuning this filter to the desired wavelength followed by a temperature change to achieve optimum output power should result in a reliable continuous tunability over 200 Å.

Using a dewar cooled by liquid nitrogen instead of the MMR refrigerator, the achievable output power was about a factor of 3 higher with a power conversion of 15%. The highest output power obtained was 32 mW ($P_p = 200 \text{ mW}$) before the spot was damaged. The different power outputs at equal temperatures of the cold finger (77K) can hardly be explained by different cooling rates, since a raise in temperature of the MMR did not decrease the output power. Therefore other causes must be responsible for the lower powers.

5. Conclusion

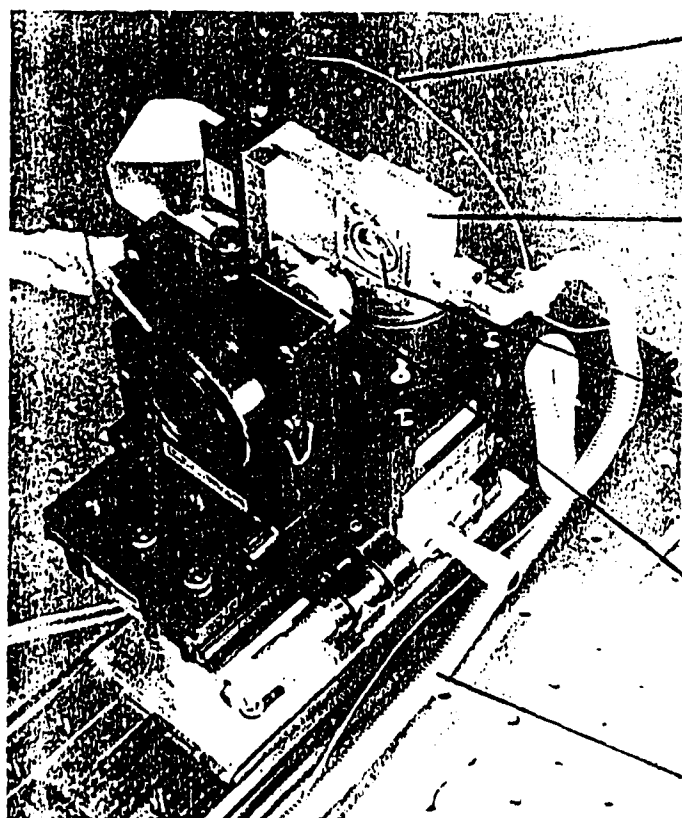
We have shown that the tested refrigerator is an attractive alternative to other dewar designs for optically pumped semiconductor lasers. For medium power requirements up to 10 mW the compactness, light weight, and precise temperature control are advantageous over those dewars operating at liquid gas temperatures only. With the the development of a nitrogen recycling system the compactness of the whole system can be further improved.

6. Acknowledgments

This work was supported by the Air Force Weapons Laboratory.

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High Pressure Line

Dewar

Mirror with Platelets

Objective

Vacuum Line

FIGURE 1

Setup of the microminiature refrigerator
and microscope objective in the CdSe Laser

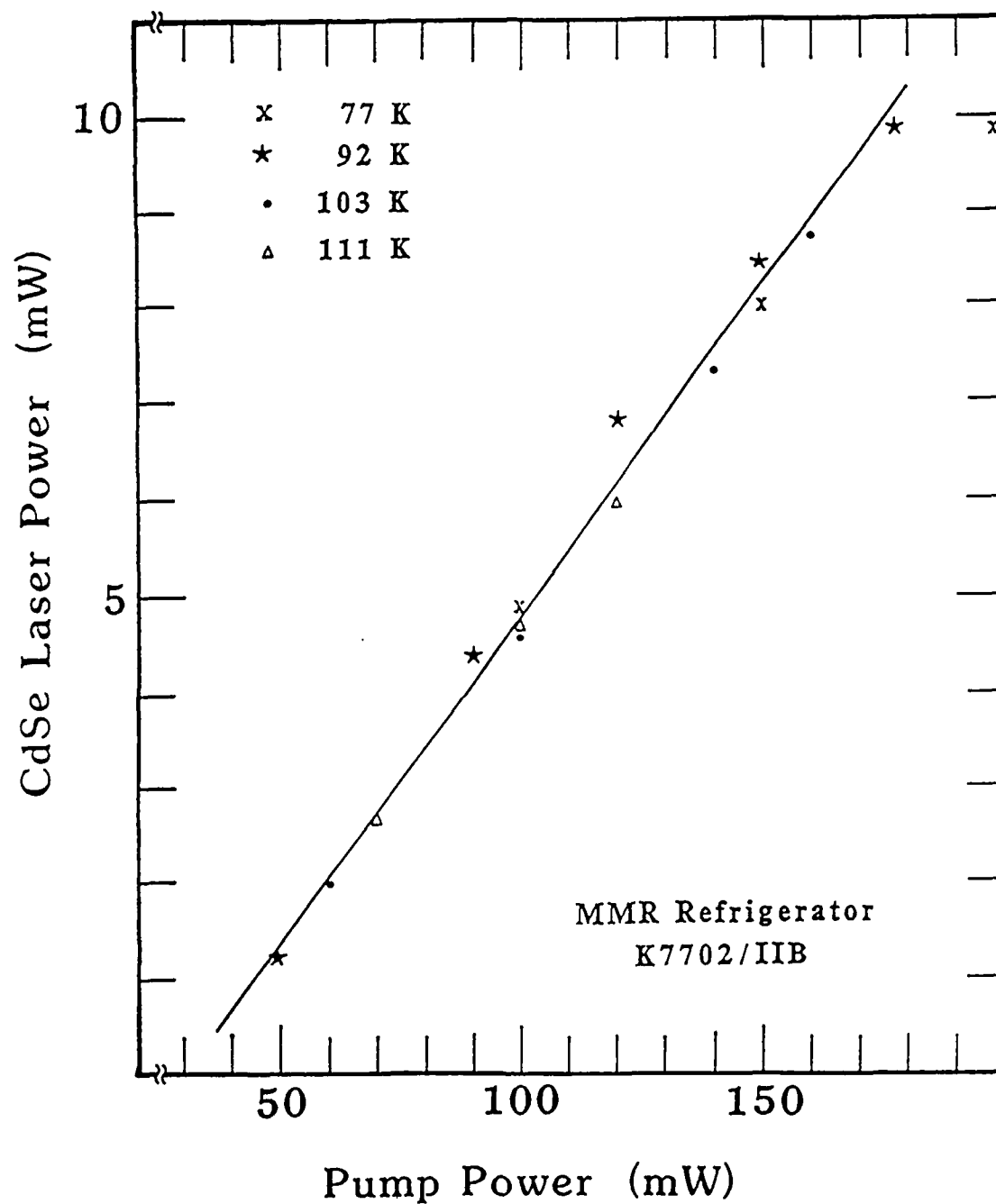


FIGURE 2

CdSe laser output versus pump power for 4 different temperatures.

All measurements were taken with the same lasing spot.

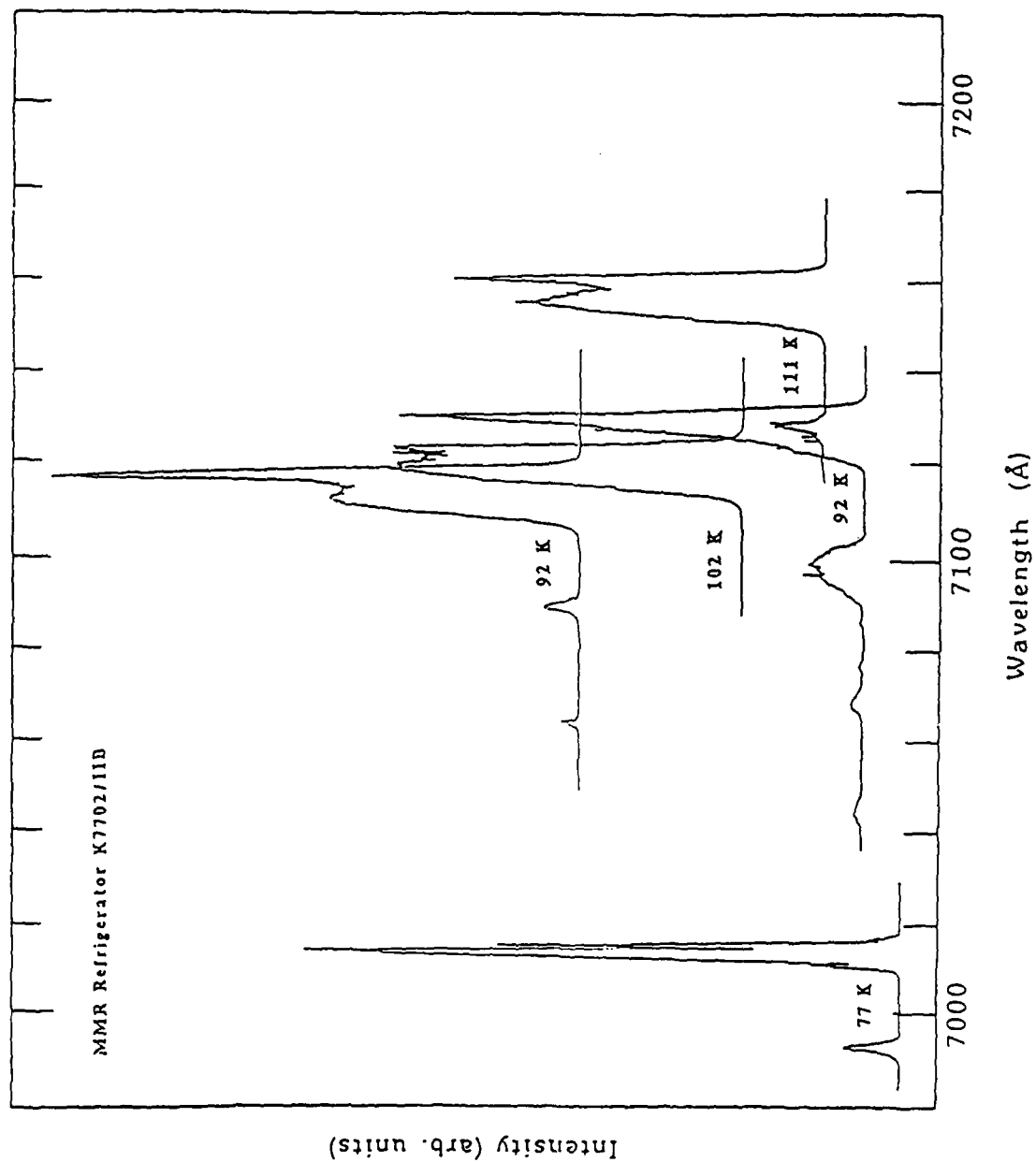


FIGURE 3

Shift in laser wavelength for four different temperatures. All spectra were recorded using 100 mW pump power. The shift of the laser line between the two spectra recorded at 92K results from a realignment of the cavity.

APPENDIX B

OPTICALLY PUMPED INTRACAVITY NONLINEAR PHASE-CONJUGATE ADAPTIVE OPTICS

1. Contributing Authors

B. Valk and M.M. Salour

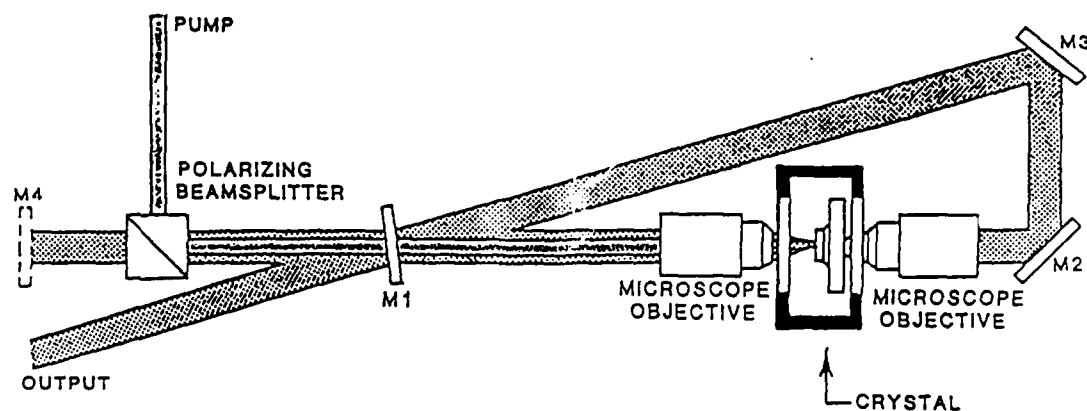
2. Abstract

Optically pumped intracavity nonlinear phase conjugate adaptive optics are theoretically investigated.

3. Introduction

Over the past few years the principal investigator has pioneered the design of optical cavities associated with optically excited semiconductor lasers. These lasers combine the advantage of an increased spectral range over dye lasers with the possibility of intracavity elements not available in diode lasers. In addition, they can operate at a variety of frequencies, including the visible and infrared regions, and with a large variety of materials. Our semiconductor laser cavity consists of an active gain medium (typically platelet of $\sim 30 \mu\text{m}$ thickness) mounted on a piece of optical quality sapphire (Figure 1). The sapphire has its axes parallel to axes of the semiconductor platelet to prevent depolarization of the laser beam. The sapphire is mounted on a copper frame attached to a cold chamber to avoid optical damage due to excessive sample heating by the pump beam. The pump beam is focused to a spot size of $\sim 5 \mu\text{m}$ by using a 10X microscope objective which also serves to collimate the crystal's fluorescence. The same type of microscope objective is used at the backside of the crystal to collimate the rear fluorescence. Mirrors M2, M3, and M4 are flat and highly reflective, while the flat mirrors used as output mirror M1 have transmissions between 0.5% and 50%. A polarizing beamsplitter distinguishes between the vertically polarized pump light and the horizontally polarized output of the

semiconductor laser. Tunability is accomplished by replacing mirror M2 with a prism and rotating either the prism or one of the mirrors.

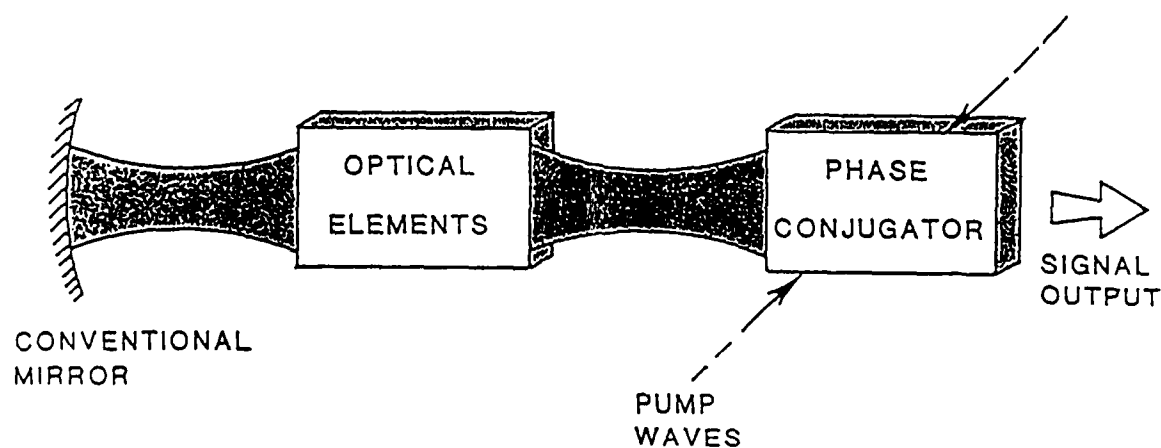


Optically Pumped Semiconductor Ring Laser

FIGURE 1

4. Theoretical Results

Figure 2 shows a general version of the proposed phase-conjugate optical resonator using four-wave mixing. The optical elements inside the resonator include lenses, dispersive elements, aberrating elements, etc., and the laser gain medium.



Phase-Conjugate Optical Resonator

FIGURE 2

This resonator is an extension of ring cavity (Figure 1) and folded resonators for semiconductor lasers, and contains an internal laser gain medium or relies on a phase conjugation reflectivity greater than unity to achieve oscillation inside the proposed cavity. Such cavities will not only cancel (or at least partially correct for) imperfections and phase aberrations in the laser medium and other optical elements inside the resonator, but will also have the added advantage of shaping novel optical wavefronts; for generating ultrashort mode-locked pulses; and for other novel applications yet to be invented and put to use.

In our experiments we utilized a similar cavity except one reflector was a self-pumped PCM. Such a ring resonator has longitudinal-and transverse-mode properties distinct from those of conventional resonators. Aside from interesting physical behavior, such a resonator has an important impact in high speed aberration correction involving turbulence. Given the dynamic behavior of turbulence, the application requires real-time aberration correction. Therefore, in our design, the PCM is characterized by a response time shorter than the characteristic time of the turbulence. In another configuration the PCM was produced by two counter propagating pump beams supplied by the pump laser.

5. Conclusions

a. Gain Medium

In order to establish the frequency and spatial properties of our phase conjugated ring cavity we need to utilize a proper gain medium and a CW (or quasi-cw) PCM. The pump beams are incident in a medium possessing a large third order nonlinearity $\chi^{(3)}$, thus the reflectivity is proportional to the square of the incident signal. Our calculations show that given an optically pumped semiconductor laser with gain values of $g_o L$, one needs a moderately efficient DFWM response to achieve the oscillation condition given by

$$\exp(2g_o L) = R_1^{-1} R_{PCM}^{-1}$$

B-1

where R_1 is the reflectivity of the output coupler and R_{PCM} is the reflectivity of PCM. The output is extracted from the regular mirror, and, in the presence of intracavity aberrations, it is this beam that will exhibit the transverse cavity mode. Certain parameters such as cavity length, the Fresnel number, and the cavity lifetime need to be optimized, and to ensure steady-state modes we are planning to operate in a CW configuration utilizing high-reflectivity CW PCM with four-wave mixing in bulk semiconductors.

To achieve oscillation, our calculation shows that the reflectivities should exceed $\sim 40\%$, consistent with the net gain in the system. Bulk materials are excellent candidates for the gain medium. In fact, using geometry of Figure 2 we should achieve reflectivities of greater-than-unity.

We have shown that these external cavities and laser medium itself when combined can be integrated and made smaller than any other type of laser to date. With increased development in microstructure technology, one is therefore impressed by the possibility of smallness conceivable with a PCR - and - semiconductor gain medium combination.

b. Output Power Consideration

If it is assumed that the four-wave conjugate signal is produced by a 2-level saturable absorption process, the output power in watts of such a resonator can be calculated as:

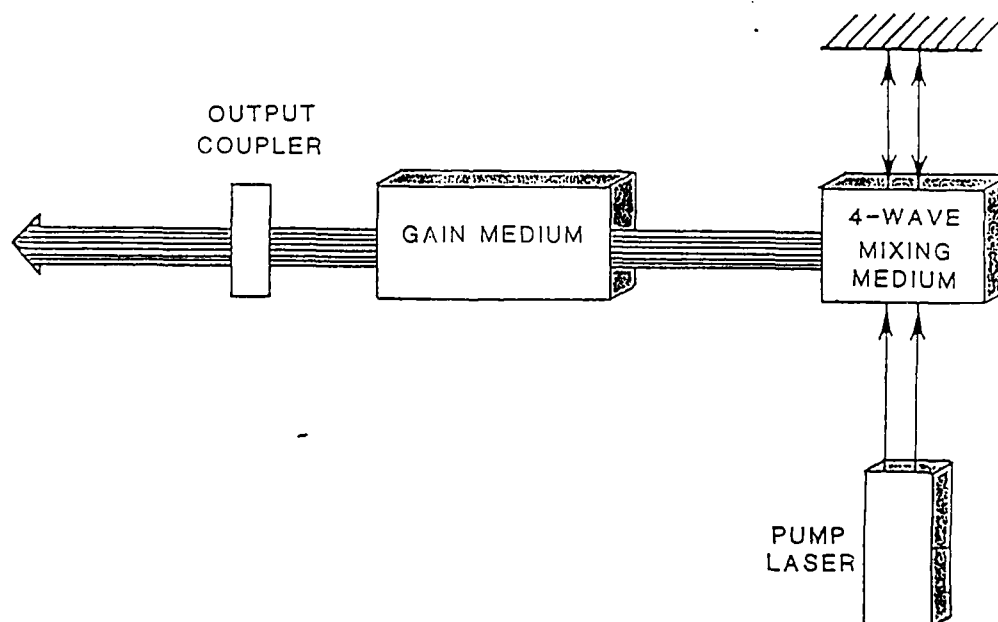
$$P_{out} = [AI_{sc}] \left[\frac{1-R}{RG_o} \right] [RR_{PCM}G_o^2 - 1] \quad (B-2)$$

where I_{sc} is the conjugate or saturation intensity (assumed to be much smaller than the saturation intensity of the gain medium), R is the reflectivity of the output coupler, R_{PCM} is the reflectivity of the PCM, A is the area of a resonator mode, L is the length of the medium, and overall system gain $G_o = e^{g_o L}$, where g_o is the small signal gain.

This type of resonator is inherently inefficient; since external pumps are required with powers typically greater than the PCR's output power. However, because of its relative simplicity the external laser-pumped configuration has been used for a number of significant experimental demonstrations of the unique properties of PCRs. With an aberrator placed inside the PCR, the output through the ordinary mirror is diffraction limited, while the output through the PCM is severely aberrated. The output frequency of the PCR is shown to be locked to that of the pump laser and independent of cavity length; furthermore, the paired half-axial modes are separated by $C/4L$ from the central frequency.

c. Resonator Design

Figure 3 shows the basic configuration of a PCR. The threshold condition is the same as for a conventional resonator, where the reflection coefficient of the PCM is the phase conjugate reflectivity determined by the four wave mixing process.



Basic Configuration Phase Conjugate Resonator

FIGURE 3

APPENDIX C

OPTICALLY PUMPED MODE-LOCKED MULTIPLE-QUANTUM-WELL LASER

1. Contributing Authors

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2. Abstract

We report the first optically pumped mode-locked $\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}/\text{GaAs}$ multiple-quantum-well (MQW) laser in external cavity. The MQW structure with a total thickness of 5 μm was grown by molecular beam epitaxy on a Si-doped GaAs substrate and was synchronously pumped by a mode-locked Kr^+ -laser (82 MHz) at 647.1 nm. The MQW laser emitted 10 ps pulses at 8085 Å with peak powers as high as 6 W. The demonstrated MQW laser combines desirable properties of quantum wells with advantages of an external cavity, such as specific bandgap design with high beam quality and the possibility of intracavity tailoring of the laser beam.

3. Introduction

Since the demonstration of optically pumped semiconductor lasers with external cavity throughout the visible and near infrared¹⁻⁴ with desirable properties such as tunability, high beam quality and generation of short pulses in mode-locked operation, it became very attractive to apply these techniques to multiple-quantum-well (MQW) structures. The optical properties of $\text{Al}_x\text{Ga}_{1-x}\text{As}/\text{GaAs}$ MQW structures have been studied extensively⁵⁻⁸ showing very strong exciton fluorescence and the multiple subbands in the GaAs wells due to the quantum confinement of electrons and holes. For many different well sizes and MQW structures made by different production techniques, lasing between the cleaved edges has been achieved by transverse pumping⁹⁻¹⁴. The main advantage

of superlattices over other optically pumped semiconductor samples is the possibility to use their very sharp resonances to shift the lasing wavelength from the fundamental band edge of GaAs. Hence, by choosing the width of the GaAs wells and the aluminum content of the barriers, these lasers can be specifically designed and optimized to certain wavelength regions.¹⁴

We report the first synchronously pumped mode-locked MQW laser with external cavity combining the quantum well properties of laser wavelength design with attractive features such as high output powers, high beam quality and pulses as short as 10 ps. Furthermore, our setup provides the possibility of various modifications of the laser by putting additional optical elements into the cavity.

4. Experiment and Results

The multiple quantum well structure used in this experiment was grown by molecular beam epitaxy (MBE) on Si-doped <100> GaAs substrates. The substrate preparation and growth of the superlattice is made by using standard procedures described elsewhere^{7,8}.

The epitaxial layers consist of 0.5 μm GaAs buffer, a 500 \AA $\text{Al}_{0.7}\text{Ga}_{0.3}\text{As}$ etch stop layer and a superlattice of 250 periods of 100 \AA GaAs and 100 \AA $\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}$. In contrast to all other reported optically pumped MQW lasers, in our experiment the superlattice is pumped longitudinally. The absorption length of the 647.1 nm pump light is about 0.5 μm at 77 K in the GaAs wells and 1.0 μm in the $\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}$ barriers^{7,8}. Hence, to provide a sufficient gain length the total MQW layer thickness should exceed 2 μm . Taking into account additional facts such as possible saturation which increases the absorption length at the high pump intensities needed to get the MQW laser over threshold and to provide enough material for sufficient heatflow from the pumped spot to the heatsink, we decided for a total MQW thickness of 5 μm . The carriers generated in the barriers by absorbing pump light also contribute to the laser process because they diffuse to the wells with a velocity¹⁵ in the order of 10^7 cm/s where they can form excitons.

A large MQW sample was cut into pieces and some of them were mounted with a transparent cyanoacrylate adhesive on a high reflective sapphire mirror with dielectric coating. Sapphire was used because of its high heat conductivity at low temperatures and the thickness of the glue film was below 5 μm keeping this heatflow barrier very small. Other pieces were coated with a 2000 Å gold film on the MQW side acting as a high reflective mirror ($R=0.94$ at 800 nm) of the external cavity. These samples were glued on an uncoated sapphire substrate. After polishing the GaAs substrate down to 50 μm a couple of circles with about 1 mm diameter were defined photolithographically. The substrate within these circles was then removed by selectively etching it down to the etch stop layer which is practically transparent to the pump and MQW laser light. Instead of removing the whole substrate, the described sample with holes provided the possibility to either pump the MQW or the Si-doped GaAs substrate, whose lasing characteristics have been published recently.⁴

The sapphire mirror with the MQW sample was attached to a copper coldfinger and cooling was provided by liquid nitrogen. The dewar with antireflection-coated windows was mounted on a translation stage, making it possible to find those spots on the sample giving the highest output powers and shortest pulses as well as shifting from the MQW laser to the GaAs laser. A 10X microscope objective (Leitz) was used to focus the pump beam onto the sample and to collect the fluorescence light. An estimation of the lasing spot diameter of 3.5 μm was possible by measuring the diameter of the holes burnt into the samples at higher temperatures. The 90% transmission of the objective at the laser wavelength is fairly low for intracavity use, but from earlier work⁴ it seems that low spherical aberration is more important than highest transmission.

As a pump source a mode-locked Kr^+ -laser was used, emitting 100 ps pulses at 647.1 nm. Because of the 150 nm spacing between the pump laser and MQW laser, it was possible to pump the MQW laser through its 90% output coupler and use a dichroic beamsplitter to separate the two beams as illustrated in Figure 1. The laser and fluorescence spectrum of the MQW was measured with a 1/2 m monochromator (Jarrell-Ash). The grating was used in second order resulting in a resolution of better than 0.5 Å. The temporal width of the pulses was measured by means of background-free autocorrelation. Since autocorrelation is most efficient with linearly polarized beams, a Brewster-plate was inserted into the cavity.

Stable average output power as high as 5mW has been obtained from the MQW laser with 10% output coupling and 55 mW pump power. The threshold is around 20 mW, however, it can vary slightly depending on the quality of the lasing spot. The laser power first increases linearly with pump power until it reaches approximately 3x the threshold. For pump powers higher than 60 mW a sharp decrease of the MQW laser power occurs which is most likely due to local heating, enhancing the nonradiative decay of excitons. An increase of the pump power from 50 mW to 70 mW and then decreasing back to 50 mW resulted in about the same output power, proving that the observed power decrease was not caused by permanent damage to the MQW layer. Using the gold coated samples, the highest achievable average power was 3.5 mW and the threshold was 25-30 mW. Scanning the pump beam over the MQW layer resulted in small changes of the laser output indicating a fairly good uniformity of the samples.

Figure 2 shows (a) the MQW laser spectrum and (b) the fluorescence spectrum. Due to the 100 Å wells three distinct free exciton transitions can be seen in (b): at 8110 Å, at 7870 Å and very weakly at 7650 Å. The peak at 8320 Å is most likely a bound exciton transition.¹⁶ These results are similar to those obtained in Ref. 10 for high pump intensities, however, they can not be compared directly because of the different MQW structures used. Lasing occurs at 8060 Å and a second weak line appears at 8300 Å. The 240 Å spacing between these lines is consistent with the free spectral range (FSR) of the Fabry Perot formed by the 5 µm MQW layer. In contrast to the 10 Å mode spacing of the GaAs-laser⁴, the FSR of the thin MQW layer is large enough to achieve single-line operation by cavity alignment only. On the longer wavelength side of the main laserline a second small peak appears 23.5 Å apart. The appearance of one or two additional lines, either about 25 Å or 36 Å separated from the main line, was strongly dependent on the pumped spot. Furthermore, the actual laser wavelength itself could shift from spot to spot giving strong evidence for well size fluctuations. However, since a well size variation of about 3 monolayers of GaAs for 100 Å wells can explain the observed lines^{6,16}, their relative weakness indicates the high quality of the 250 periods of the MQW structure used. The obtained results

are also in good agreement with recently published photoluminescence studies¹⁷ which showed a similar sensitivity of exciton transitions on well size fluctuations. A better single line operation and more reproducible laser wavelength at a given sample temperature should be obtainable by using 200 Å wells because the relative shift of the energy levels of the electrons is less sensitive to well size variations⁶ and only half as many wells are involved.

An additional effect on the lasing wavelength was caused by the pump beam. Increasing the pump power by 50 mW resulted in a red shift of the laser wavelength of 35 nm indicating a severe local heating of the pumped spot. Furthermore, the line broadened by about a factor of 2.7 and additional lines appeared at pump powers higher than 40 mW. To determine the possible temperature tuning range we deliberately let the dewar warm up and observed a shift of the laser wavelength up to 8460 Å. A measurement of the temperature was not possible in this experiment because no sensor could be mounted in the dewar used. Together with the results reported on the Si-doped GaAs laser our setup provides a potential tuning range from 8060 Å to 8650 Å.

The temporal pulsewidth has been measured by background-free autocorrelation. From the shape of the autocorrelation trace shown in Figure 3 we conclude that single-sided exponential pulses are produced by the MQW laser when tuned to the shortest pulses, which is in agreement with similar results obtained with dye lasers.¹⁸ From the 20 ps width of the autocorrelation trace, the calculated pulse width of the MQW laser is 10 ps. Together with a spectral width of 3 Å, the resulting time-bandwidth product is 1.37. The peak power can easily be determined from the average power by multiplication with the inverse duty cycle of 1200, given by the repetition rate and pulse width. Hence, with 5 mW average power, the maximum achievable peak power of our laser is 6 W.

5. Conclusions

We have demonstrated synchronously pumped mode-locked operation of a multiple-quantum-well structure in external cavity. The achieved high output powers are very promising to achieve similar results with other MQW structures

such as $\text{Ga}_{0.47}\text{In}_{0.53}\text{As} / \text{Al}_{0.48}\text{In}_{0.52}\text{As}$ in which lasing already has been reported with cleaved facets at $1.55 \mu\text{m}$.¹⁹ Furthermore, the external cavity provides the possibility of further optical intracavity studies of various MQW structures. The strong sensitivity of the wavelength on the lasing spot can be avoided by using thicker well sizes. However, the emitted wavelength would also shift to longer wavelength. On the other hand one can take advantage of the well size sensitivity by producing wells with steadily increasing size of a few monolayer which should give a very broad fluorescence spectrum. By using a birefringent filter in the cavity, a fairly large tuning range at one temperature can be expected.

Strong and readily saturable MQW excitonic emission has been observed at room temperature,²⁰ therefore, lasing in an external cavity without the need for cryogenic temperatures should be possible by resonant pumping close to the bandgap. Pumping with a commercially available diode laser at room temperature can then lead to an integrated device having major applications in a variety of ultra high speed optical signal processing technologies.

6. Acknowledgments

The authors greatly acknowledge helpful discussions with D.C. Reynolds concerning the spectroscopic data, D. Bebelaar for providing a 20 GHz GaAs photodiode, and D.J. Olson and W. Kopp for technical assistance. This work was supported by the Air Force Weapons Laboratory.

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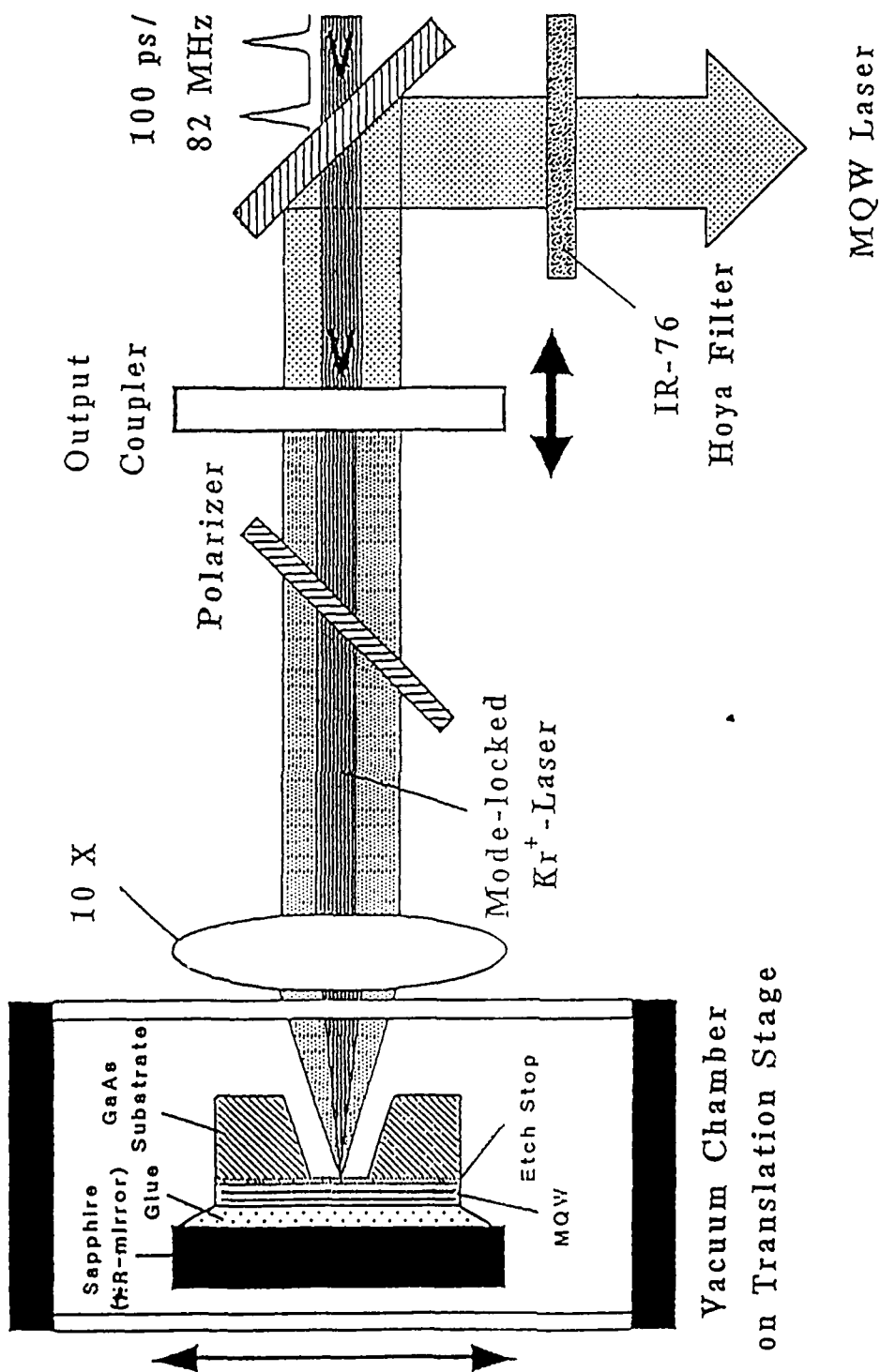


FIGURE 1

Experimental Setup

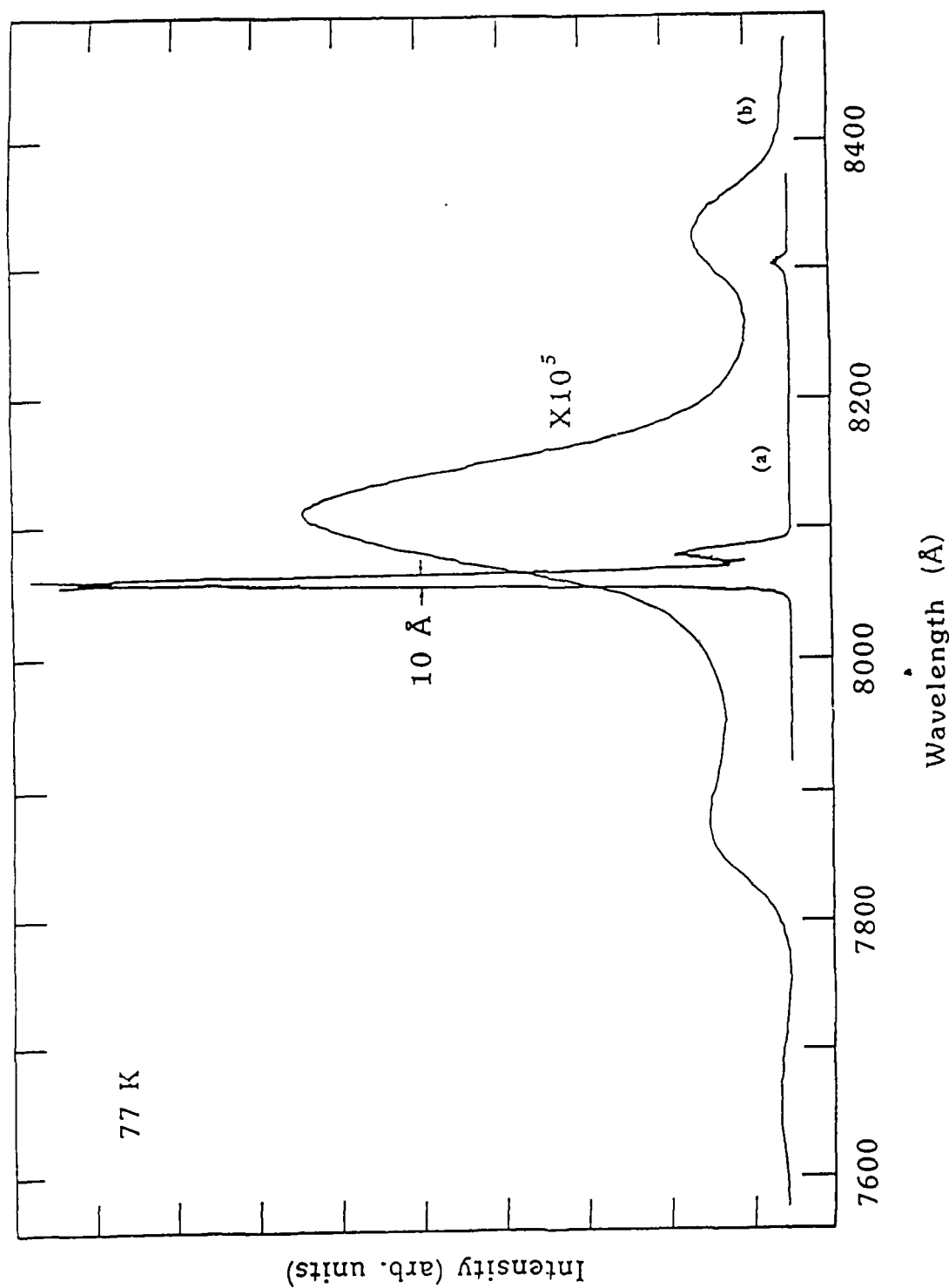


FIGURE 2

- (A) Laser spectrum (sample with Au-coating) and
- (B) Fluorescence spectrum when the output coupler was removed

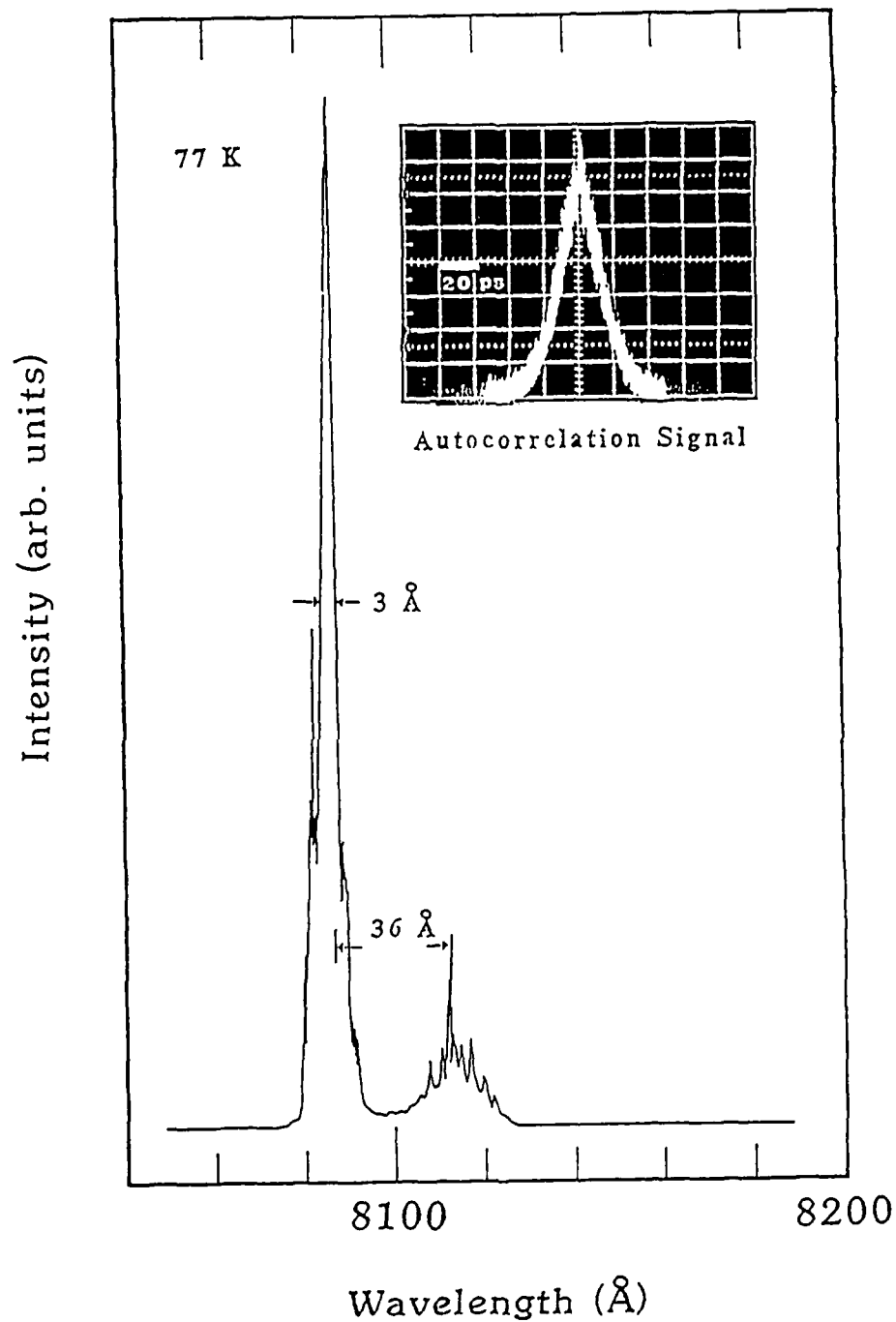


FIGURE 3

Autocorrelation trace with a width of 20 ps and the accompanying laser spectrum. The calculated pulse width of the MQW laser is 10 ps and the average output was 4.5 mW.

APPENDIX D

OPTICALLY PUMPED TUNABLE MODE-LOCKED Si-DOPED GaAs LASER

1. Contributing Authors

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2. Abstract

Mode-locked operation of Si-doped bulk GaAs in external cavity was achieved by synchronous pumping with a Kr^+ laser at 647.1 nm. High beam quality and peak powers of up to 3.3W are unique features of this laser. The spontaneous spectrum is narrower than those of dyes, allowing a stabilized single-frequency operation with fewer wavelength selective elements, while tunability over a range of 300 Å was achieved by varying the temperature.

3. Introduction

Optical pumping of semiconductors has the advantage over diode and dye lasers in that virtually any direct-band-gap semiconductor can be used, thereby increasing the available spectral range. Recently mode-locked laser action in external cavity of synchronously pumped semiconductor materials like CdS, CdSe, InGaAsP and HgCdTe has been demonstrated in the wavelength range of 0.49 μm to 2 μm .¹ Mode-locked lasing of thick GaAs bulk crystals has also been observed using a two-photon synchronous pumping configuration.² These lasers have advantages over dye lasers because of the lack of dye instability in the infrared and in addition no jet fluctuations are present, eliminating a very strong source of noise, and they can be operated completely in vacuum. Furthermore, the spontaneous spectrum is narrower than those of dyes, allowing a stabilized single-frequency laser to operate with fewer wavelength selective elements, while tuning can be done by varying the temperature.

However, the wavelength range spanning from 0.49 - 2 μm is not yet covered completely by mode-locked semiconductor lasers due to the lack of available high quality semiconductor materials in platelet form of any desired composition.

We report the development of a CW mode-locked GaAs semiconductor platelet laser whose output frequency and power characteristics provide an attractive tunable source in the near infrared. The laser reported here has the advantage of high beam quality and high output powers compared with other semiconductor lasers operating in the 800 - 900 nm spectral range.³

4. Experiment and Results

Figure 1 illustrates the experimental setup. A mode-locked Kr^+ laser was used as pump laser emitting 100 ps pulses at 647.1 nm with a repetition rate of 82 MHz and a peak power of 144 W. The pump beam passed: 1) a telescope to compensate for chromatic aberration of the microscope objective, 2) a variable attenuator, 3) a dichroic beamsplitter to separate the GaAs laser beam from the pump beam and 4) the output coupler of the GaAs laser before it was focused onto the GaAs substrate with a 10X microscope objective (Leitz). The pump powers given in the following are always measured in front of the objective taking into account all losses and the maximum average pump power was 300 mW.

The GaAs platelets with a thickness of 100 μm were mounted onto a high reflecting sapphire mirror with a thin film of silicon oil. The GaAs was doped with Si and of a high optical quality, used as substrate to grow Multiple Quantum Well (MQW) superlattices on it.^{4,5} The results reported in this letter have been taken with a sample having a 1 μm MQW layer on its backside. However, we verified spectroscopically that the influence of the MQW on the GaAs laser is negligible because all pump light is absorbed in the substrate before it could reach the MQW layer and the fluorescence light is absorbed by the MQW only below 8300 Å.

The high reflecting mirror with the attached GaAs platelets was mounted on a copper coldfinger of a liquid nitrogen dewar. The dewar itself was sitting on a translation stage for the purpose of alignment and shifting the pumped spot over

the sample. The windows of the dewar were coated with a broadband antireflective (AR) coating for the GaAs laser and pump laser. Output couplers of $R = 0.90$ and $R = 0.97$ were used for our measurements and no tuning or polarizing elements were inserted into the cavity. The GaAs laser output was analyzed by a 1/2 m Jarrell Ash monochromator and the pulse width was measured with an autocorrelator. For the temperature tuning of the laser, the dielectric coated sapphire mirror with the platelets was mounted in a cryogenic microminiature refrigeration system (MMR-Technologies K2205) which provided the opportunity to set the temperature between 77K and 300K.

Figure 2 shows (A) the fluorescence spectrum and (B) the laser spectrum. The fluorescence has always been measured with the output coupler removed and is characterized by Fabry Perot modes due to the platelet thickness of about 100 μm and the 30% reflectivity at each surface of the substrate. With the $R = 0.90$ output coupler an average laser output of up to 5 mW could be achieved. The laser spectrum (B) usually showed about 7 modes, depending on the excited spot and alignment of the cavity. The linewidth of each mode is 1.5 \AA (FWHM) and lasing occurred always at the maximum or, due to a lower reabsorption, on the red side of the fluorescence spectrum. We observed that the actual laser wavelength was not only dependent on the temperature of the whole sample but also on the the lasing spot itself. Since lasing occurs either on a free or bound exciton transition, the non uniform concentration of impurities in the GaAs sample leads to a wavelength shift by moving from one spot to another. Furthermore, the platelet acts as an intracavity Fabry Perot etalon, tuning the laser to its maximum transmission.

Figure 3 shows spectra of: (A) GaAs substrate pumped through the MQW layer when lasing, (B) the according fluorescence spectrum, (C) GaAs substrate with MQW structure facing the high reflective mirror, and (D) GaAs substrate with removed MQW (selective etching). Trace (B) shows a strong maximum at 7950 \AA due to a strong fluorescence from the MQW layer. Lasing did not occur around this maximum as one might expect but at 8350 \AA which is the same wavelength as when pumped through the substrate side (compare Fig. 2). Two reasons can explain this result: 1) The luminescence radiation produced within the MQW layer has to penetrate the substrate before it is reflected at the back mirror and light below

8200 Å is reabsorbed by the GaAs substrate, 2) the gain in the MQW layer is not high enough to get the laser over threshold within the layer thickness of 1 µm. Pumping a GaAs sample with the MQW structures removed resulted in spectrum (D) without the rapid fluorescence decrease below 8300 Å, which is most likely caused by reabsorption in the MQW layer on the backside of the GaAs platelet [figure 2(A) and 3(C)]. However, no lasing spot could be found on this specific sample.

With the $R = 0.90$ output coupler, average powers as high as 5 mW could be achieved with a pump power of 300 mW. The power conversion efficiency is about 1% between 1 mW and 5mW with a $R = 0.90$ output coupler and 0.4% when a $R = 0.97$ mirror was used. The threshold pump power was around 120 mW for the 90% output couplers and 80 mW for the 97% mirror. However, a precise measurement of the threshold was not possible because of its strong dependence on the pumped spot. Furthermore we often found that lasing spots were isolated on the sample such that lasing happened to stop after shifting the sample a few microns. Despite the relatively low efficiency due to the 20% intracavity loss of the microscope objective, the achieved powers are much higher than that of other optically pumped GaAs lasers.^{2,6} Using doublet lenses [Melles Griot D6LAI] designed and AR coated for work with diode lasers at 830 nm, failed to achieve any lasing, indicating that a well corrected optical system is more important than using lenses with minimum transmission loss. However, microscope objectives specially designed for intracavity use at the laser wavelength should result in much higher output powers.

The pulsewidth of the laser was determined with an autocorrelator to be 18 ps (FWHM) assuming single-sided exponential pulses. This measurement correlates with the obtained spectral data of the laser linewidth of 1.5 Å, resulting in a time-bandwidth product of 1.16. Thus, the Fabry Perot etalon formed by the GaAs itself reduces the laser bandwidth too much to produce pulses shorter than 10 ps. Using AR coated platelets which removes the etalon effect leads to an increased bandwidth and pulses as short as 7 ps should be achievable.² Additionally, single mode operation as well as fine wavelength tuning with prisms or Lyot filters would be possible

Wavelength tuning between 8350 Å and 8650 Å has been accomplished by controlled setting of the temperature between 77K and 160K. No lasing occurred at temperatures higher than 160K. The observed wavelength shift of about 3 Å/K is in good agreement with⁶ but about twice of that found for the CdS lasers.¹

5. Conclusions

We have demonstrated the first mode-locking of Si doped bulk GaAs platelets producing 18 ps pulses with peak powers of up to 3.3 W. AR coating of the crystals may yield a larger intracavity bandwidth and thus even shorter pulses. Furthermore, using GaAs platelets grown by liquid phase epitaxy or similar techniques, having greatly reduced impurity concentration compared to the substrates used, should lead to a better controlled laser wavelength characteristic and CW operation. The GaAs laser fills a gap in the row of synchronously pumped semiconductor lasers in the important wavelength interval between 800 nm and 900 nm. With our pumping scheme a very good beam quality could be achieved which is one of the great advantages over all other GaAs lasers. In addition, other doped semiconductor materials can be used for extended tunable picosecond pulse generation throughout the visible and near infrared.

6. Acknowledgments

The authors gratefully acknowledge the preliminary studies of J. M. Costa and the technical assistance of D. J. Olson. This work was supported by the Air Force Weapons Laboratory.

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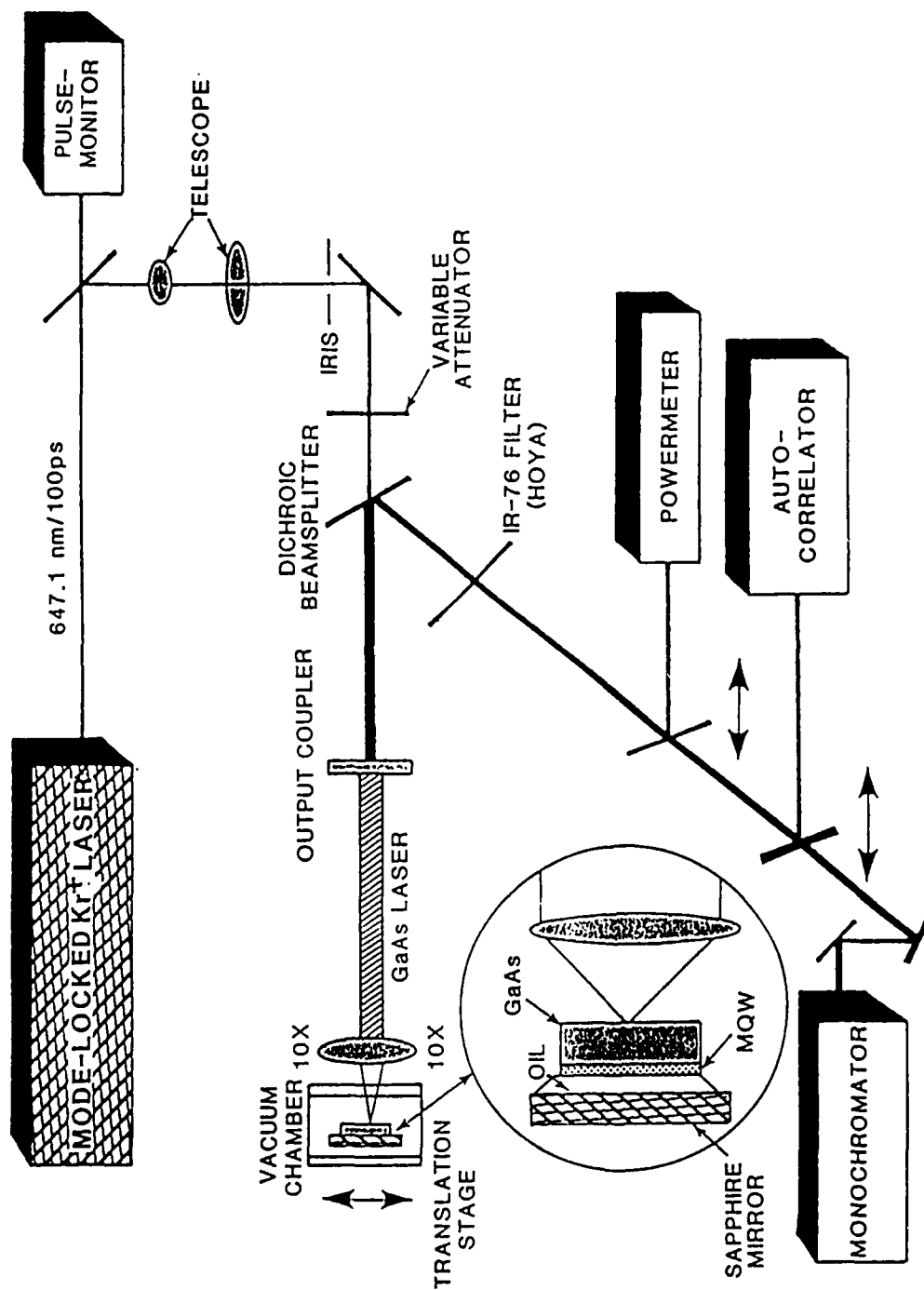


Figure 1:

Experimental setup. IR-76 is a sharp cut filter transmitting at wavelengths longer than 760 nm.

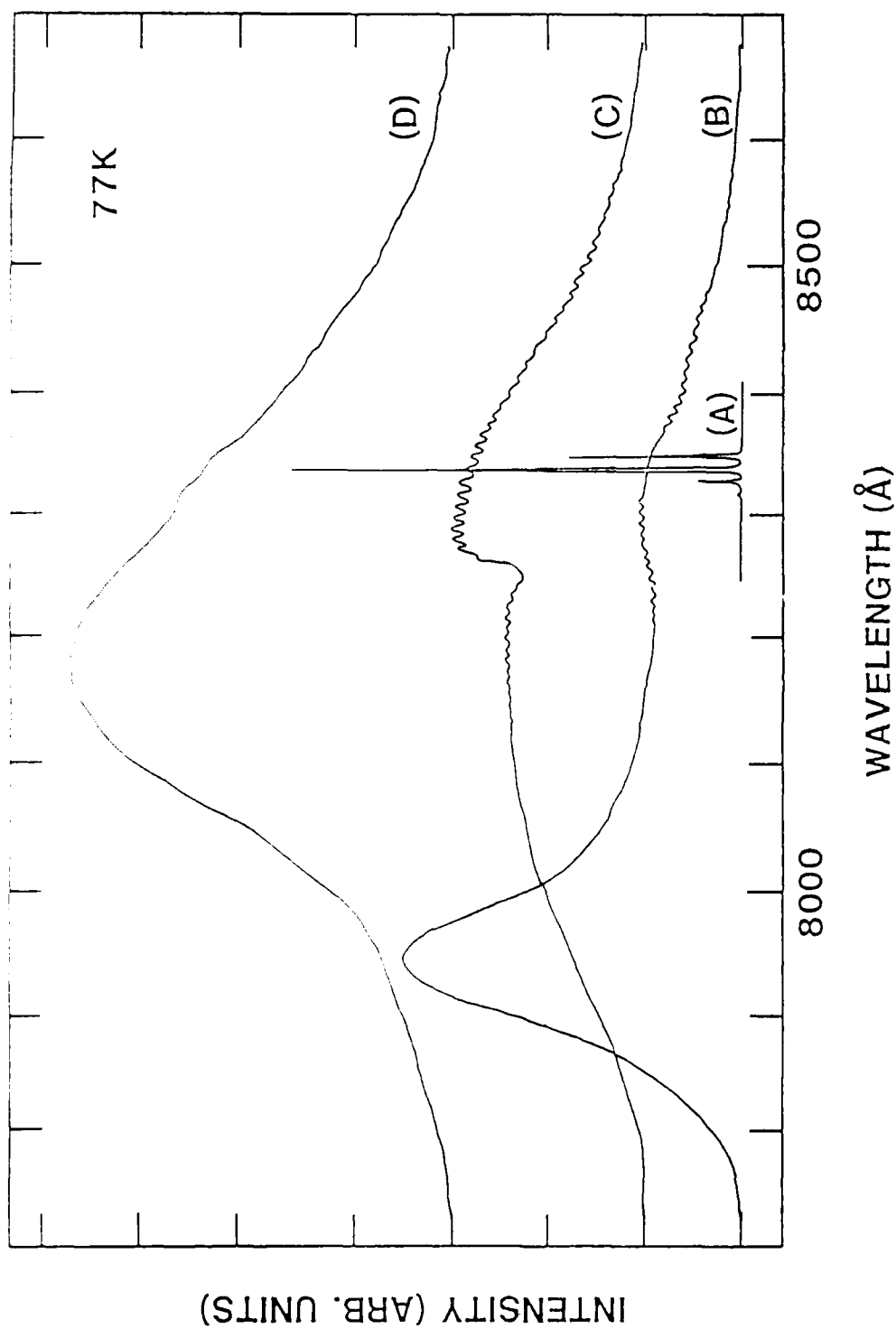


FIGURE 2

Fluorescence and laser spectrum of Si doped GaAs substrate (MQW layer facing high reflective mirror): Fluorescence spectrum (A) measured with the output coupler removed and a 106 times higher sensitivity compared to the laser spectrum (B). The latter was obtained with a 90% output coupler and 380 mW average pump power resulting in 3 mW GaAs Laser power.

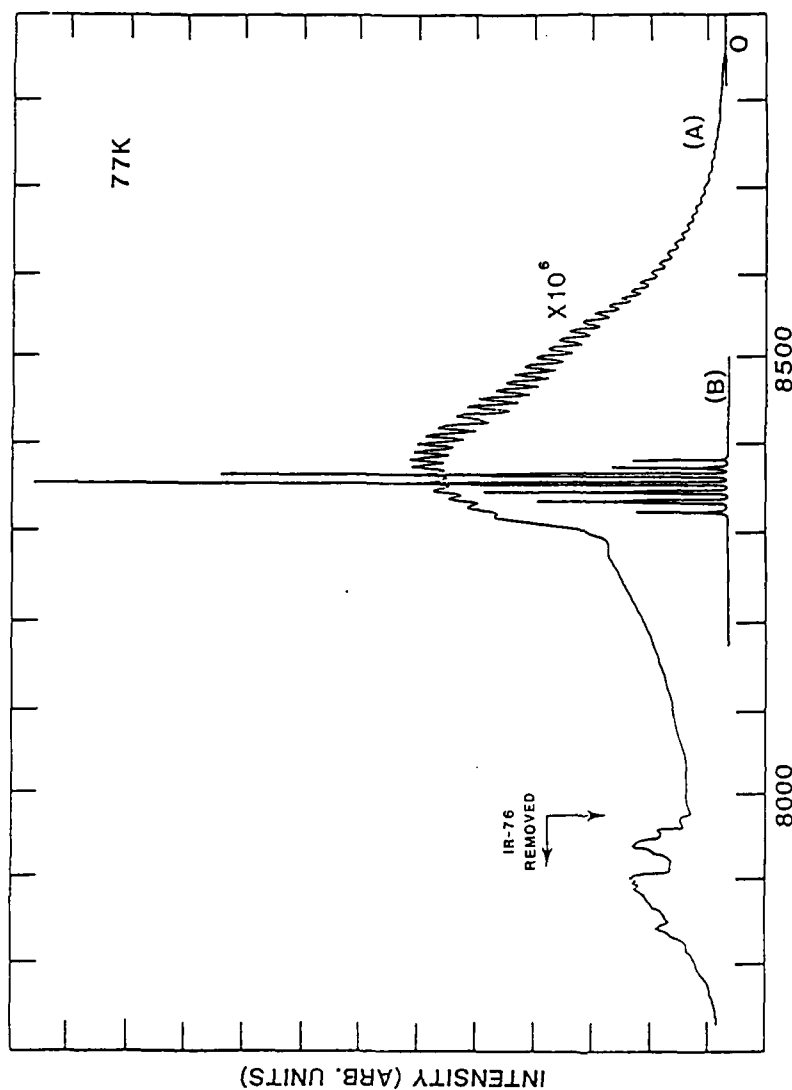


FIGURE 3

WAVELENGTH [Å]

(A) Laser spectrum of GaAs substrate pumped through the MQW side (80 Å GaAs/60 Å $\text{Al}_{0.4}\text{Ga}_{0.6}\text{As}$ /70 periods)

(B) Fluorescence spectrum of the sample used in (A) but with output coupler removed and sensitivity increased.

(C) Fluorescence spectrum GaAs sample used in (A) and (B) but MQW side facing the high reflective mirror.

(D) Fluorescence spectrum of a sample where the MQW was removed by selective etching.

END

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